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INTERNATIONAL APPLICATION PUBLISHED U

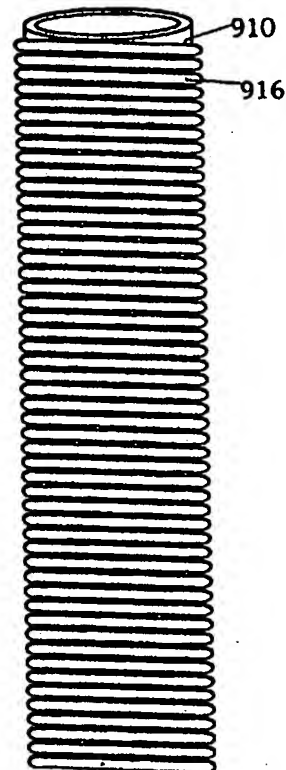
WO 9604690A1

(51) International Patent Classification 6 : <b>H01M 8/10, 6/00</b>		A1	(11) International Publication Number: <b>WO 96/04690</b>
			(43) International Publication Date: 15 February 1996 (15.02.96)
(21) International Application Number: PCT/US95/09947		(81) Designated States: CA, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).	
(22) International Filing Date: 4 August 1995 (04.08.95)		<b>Published</b> <i>With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i>	
(30) Priority Data: 08/285,945 4 August 1994 (04.08.94) US 08/286,131 4 August 1994 (04.08.94) US			
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(54) Title: TUBULAR FUEL CELLS AND THEIR MANUFACTURE

## (57) Abstract

A lightweight hydrogen fuel cell assembly employing a wet perfluorosulfonic acid electrolytic membrane (918), prone to swelling, has a tubular shape (910) and inner (916) and outer (920) helically wound electrodes which assist compression of the electrolytic membrane (918) and provide novel and efficient current collection means. Disclosed embodiments include a self-contained portable fuel cell in which the cell is shaped to accommodate a canister of hydrogen fuel and an array of cells arranged around a common hydrogen fuel tank or canister.



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## TUBULAR FUEL CELLS AND THEIR MANUFACTURE

### TECHNICAL FIELD

5 The present invention relates to hydrogen power cells of the type which receive hydrogen or other gaseous combustible fuel and produce electricity electrochemically. More particularly, it relates to a wet-electrolyte type of fuel cell which can be rapidly initiated even at room  
10 temperature and is lightweight and portable.

### BACKGROUND

Hydrogen fuel cells having a layered electrode structure in which a solid-phase proton-transporting electrolyte is  
15 sandwiched between a porous anodic electrode and a porous cathodic electrode, are known for example from Adlhart U. S. Patent No. 4,175,165. Such cells employ catalytic zones at the electrodes to disocciate hydrogen and oxygen molecules into the reactive atomic form. Cell efficiency  
20 is dependent upon continuous extensive surface contact at both electrode- electrolyte interfaces. Additionally, all-important safety considerations require that the cell be tightly sealed against leakage of potentially explosive gaseous fuels such as hydrogen. A problem with wet-

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5 electrolyte fuel cells is that swelling of the electrolyte caused by accumulating water can readily cause fuel leakage or impede generation efficiency, or both.

10 Adlhart discloses a fuel cell comprising a stack of grooved bipolar cell plates bolted together and secured with tension straps. Although quickly operational at room temperature, Adlhart's construction employs sturdy steel or alloy structural members resulting in a heavy and bulky construction designed to prevent fuel leakage. Adlhart's  
15 construction is cumbersome, expensive, hard to manufacture and does not provide an easily portable electricity source of substantial capacity.

In my U.S. Patent No. 5,336,570 dated August 9, 1994, the  
20 disclosure of which is hereby incorporated herein by reference thereto, I disclosed a lightweight and portable hydrogen fuel cell of the proton-exchange membrane type which resists swelling of the membrane by clamping the membrane between two catalytic electrodes in a tubular or  
25 frusto-conical configuration, obtaining improved hydrogen sealing and breathability. Although this construction is significantly effective in achieving its design objectives, better engagement between the electrodes and the electrolytic membrane would be desirable. Also, there are  
30 difficulties in collecting generated currents without undue losses. With the need for high current output, and an operating voltage of only about 0.7 volts per cell, contact resistances and resistance encountered in the plane of the electrode by currents flowing in the electrode to a  
35 collection terminal or terminals at its periphery can generate significant losses. A solution to these problems of electrode-membrane engagement and current collection would be desirable. Further drawbacks of the constructions set forth in my U.S. Patent '570 relate to ease and cost of  
40 manufacture. It would furthermore be desirable to have a fuel cell of the type disclosed in my Patent '570 which was easier and less expensive to manufacture.

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5 Described in more detail below in connection with Figures  
1-2 of the drawings are two embodiments of fuel cell  
employing an externally wound filament of plastic-coated  
glass fiber to exert an evenly distributed clamping  
pressure on the electrodes. These embodiments were  
10 disclosed in my International PCT application No. WO  
94/05051 published on 3 March 1994 as Figures 19 and 20  
thereof, which International application was based on my  
U.S. patent application S.N. 08/015,411 which matured into  
the aforementioned U.S. Patent No. 5,336,570. They do not  
15 overcome the above-described current collection problems.

Wilson et al. in "High Performance Catalyzed Membranes of  
Ultra-Low Pt Loadings for Polymer Electrolyte Fuel Cells"  
J. Electrochem. Soc. vol. 139 No. 2 February 1992 disclose  
20 catalyst film and electrolytic membrane structures useful  
in the practice of this invention.

Vanderborgh et al. in a paper prepared for Belvoir  
Research, Development and Engineering Center, Fort Belvoir,  
25 VA entitled "ANALYSIS OF FUEL CELLS, REACTANT DELIVERY  
SYSTEMS, AND SYSTEM INTEGRATION FOR INDIVIDUAL POWER  
SOURCES", numbered "LA-UR-93-345" discuss and disclose  
ancillary systems and engineering, relating in particular  
to management of fluids such as coolant air, source gases  
30 and moisture, which teaching can also be useful when  
practicing certain embodiments of this invention.

#### SUMMARY OF THE INVENTION

In accordance with the invention, an easy to manufacture,  
35 light-weight fuel cell with structural current collectors  
that contact the cells electrodes over an extended area and  
promote engagement of the electrodes with the cell's  
electrolytic membrane, is provided. A method of  
manufacturing the fuel cell is also provided.

40 In one aspect the invention provides a wet-operating  
electrolyte, curved shape, oxygen-reduction fuel cell  
comprising gas-pervious, curved current-collecting

5 electrodes shaped to mate one with another, gas-  
dissociating catalyst zones at each electrode and a proton  
transport electrolytic member constrained between the  
current collecting electrodes, the current-collecting  
electrodes are load-bearing structures acting to compress  
10 the electrolytic member characterized in that at least one  
of the electrodes includes a coiled winding acting to  
assist compress the electrolytic member.

15 Preferably, the fuel cell has a generally tubular shape  
with tubular components, each the electrode comprising  
concentric tubular coils, the electrolytic member being  
compressed between the tubular coil electrodes.

20 Preferably also, the fuel cell comprises a porous gas  
diffusion layer, one for each current collector, to spread  
gas permeating the current collectors for uniform delivery  
to catalyst layers adjacent the electrolytic member. The  
gas diffusion layers can comprise carbon black in a porous  
conductive binder.

25 In another aspect the invention provides a hydrogen fuel  
cell which is shaped to receive and embrace a hydrogen  
supply canister to provide a self-contained portable  
electricity generating unit. The fuel cell can include the  
30 hydrogen supply canister, the hydrogen supply canister  
having a volume and being received into the fuel cell to an  
extent of at least one half of that volume.

In another aspect, the invention provides a method of  
35 manufacturing a hydrogen fuel cell comprising a self-  
supporting shaped, layered electrode structure in which a  
solid-phase proton-transporting electrolyte is sandwiched  
between a porous anodic electrode and a porous cathodic  
electrode, the method comprising the steps of

40 a) coating a first, shaped self-supporting electrode  
with a curable, liquid-phase, proton-transporting  
electrolytic material to provide an electrolytic  
coating;

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- 5           b)    curing the electrolytic coating to the solid phase;
- c)    assembling the coated electrode with a second, mating, shaped electrode to provide the layered structure;
- 10          d)    and assembling the electrode structure with a support base.

          Preferably, the method comprises a further step of coating the first electrode with a catalyst-containing curable, liquid-phase proton-transporting material. In a preferred embodiment, the curing step has two stages: a first, solvent-evaporation stage at a moderately elevated temperature, and a second purification or decontamination stage at a higher temperature.

20

The invention also provides a method of manufacturing a such a fuel cell comprising the steps of:

- a)    forming a first gas-pervious, load bearing, current collecting electrode to a first shape;
- 25          b)    forming a second gas-pervious, load bearing, current collecting electrode to a second shape mateable with the first shape; and
- c)    assembling the first and second current-collecting electrodes with the electrolytic member into a self-supporting structure;
- 30

wherein each electrode comprises an open-work load-bearing metal structure, formed for example of titanium.

Preferably, the metal structure is selected from the group consisting of a coiled winding, expanded metal and metal braiding.

35

Preferably, one or more of the fuel cell components is shaped around a former and the method can comprise inserting plugs at the ends of the fuel cell to seal the fuel cell against loss of combustible gas.

40

#### BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the invention will now be described, by

5 way of example, with reference to the accompanying drawings, in which:

10 Figure 1 is a cross-sectional view of an embodiment of hollow tubular fuel cell according to the prior art, which fuel cell employs an external filament winding and internal support member;

Figure 2 is a side elevation of another embodiment of fuel cell according to the prior art, in which a stacked flat plate fuel cell assembly is wound with an external filament;

15 Figure 3(a) is a perspective view of a first hollow member in accordance with another embodiment of the inventive hydrogen fuel cell;

Figure 3(b) is a cross-sectional view of the first hollow member shown in Figure 3(a);

20 Figure 4(a) is a perspective view showing a first conductive winding wound around the first hollow member shown in Figure 3(a);

Figure 4(b) is a cross-sectional view of the first hollow member and the first conductive winding shown in Figure 4(a);

25 Figure 5(a) is a perspective view showing an electrolyte member disposed around the first conductive winding;

30 Figure 5(b) is a cross-sectional view of the electrolyte member, the first conductive winding and the first hollow member shown in Figure 5(a);

Figure 6(a) is a perspective view showing a second conductive winding wrapped around the electrolyte member;

35 Figure 6(b) is a cross-sectional view of the second conductive winding, the electrolyte member, the first conductive winding and the first hollow member shown in Figure 6(a);

40 Figure 7(a) is a perspective view showing a second hollow member disposed around the second conductive winding;

Figure 7(b) is a cross-sectional view showing the second hollow member, the second conductive



5 winding, the electrolyte member, the first  
conductive winding and the first hollow member  
shown in Figure 7(a);

Figure 8(a) is a cross-sectional view showing male  
and female end caps prior to installation on the  
10 inventive hydrogen fuel cell;

Figure 8(b) is a cross-sectional view of a male end  
cap modified for series connection;

Figure 9 is a cross-sectional view showing two  
joined adjacent hydrogen fuel cells;

15 Figure 10 is an isolated enlarged view schematically  
showing the first conductive winding, the  
electrolyte member and the second conductive  
winding;

Figure 10(a) is a perspective view of a modified  
20 conductive winding;

Figure 11 is a cross-sectional view showing male  
and female end caps prior to installation in  
accordance with an alternate construction;

Figure 12(a) is a top plan view of a multiple fuel  
25 cell assembly in accordance with another aspect  
of the present invention;

Figure 12(b) is a bottom plan view of the multiple  
fuel cell assembly shown in Figure 12(a);

Figure 12(c) is a view similar to Figure 12(a) of  
30 another embodiment of fuel cell assembly;

Figure 12(d) is a view similar to Figure 12(c) of the  
fuel cell assembly of Figure 12(c);

Figure 13(a) is an isolated side plan view showing the  
fuel cells of the multiple fuel cell assembly  
35 shown in Figure 12(a);

Figure 13(b) is an isolated side plan view showing a  
hydrogen gas supply tank of the multiple fuel  
cell assembly shown in Figure 12(a);

Figure 13(c) is a schematic view similar to Figure  
40 13(a) of a multiple fuel cell assembly equipped  
with fluid flow management means;

Figure 14 is a vertical cross-sectional view of a  
portable hydrogen fuel cell designed to

5 accommodate its own hydrogen supply in the form  
of a quick release hydrogen bottle;  
Figure 15(a) is a schematic sectional views of a  
further embodiment of tapered tubular fuel cell;  
Figure 15(b) is a schematic view of an inner housing  
10 component of the fuel cell shown in Figure 15(a);  
Figure 15(c) is a schematic view of an outer housing  
component of the fuel cell shown in Figure 15(a);  
Figure 15(d) is a similar view of the fuel cell of  
Figure 15(a) after application of seals to the  
15 ends of the cell;  
Figure 15(e) is an alternative embodiment of electrode  
diffusion tube for use in the fuel cell assembly  
of Figure 15(a); and  
Figure 15(f) is an enlarged partial sectional view of  
20 the layered wall structure of the fuel cell of  
Figure 15(a).

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred embodiments of the invention comprise a hydrogen  
25 powered electricity generating cell incorporating a  
plurality of layers shaped laminar members each having  
relatively small thickness and an extensive active area of,  
for example, approximately 75 square centimeters, in the  
case of a tubular cell about 10 cm. long and averaging  
30 about 7.5 cm. diameter. Such a cell can generate  
approximately three watts of electricity at approximately  
0.7 volts.

Referring to the prior art embodiment of Figure 1, an inner  
35 anode 814 and an outer cathode 818 have sandwiched between  
them an electrolytic member 816, these members being formed  
of materials such as those having the characteristics  
described elsewhere herein. This composite tubular fuel  
cell assembly is supported in end caps 822 and 824 each of  
40 which is internally threaded at 832 for connection of a  
hydrogen supply which can be passed from one cell to the  
next.

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5 Within tubular anode 814 is a tubular, porous support tube  
840 which is rigid and has sufficient strength to bear the  
clamping pressure provided by external tightly wound  
filament 842. The presence of porous tube 840 is optional  
depending upon the structural strength of the anode 814 and  
10 of cathode 818. Porous tube 840 can be constructed of any  
suitable material, for example, it can be formed of rigid  
paper or ceramic, or may constitute a self-supporting  
screen of a rigid plastic material. Although, a metallic  
screen could be used, from a mechanical point of view it is  
15 preferred to avoid the use of metals in contact with  
hydrogen, where possible. Other structures, such as cross-  
members or bracing can also provide the support functions  
of porous tube 840. Porous tube 840 is also accommodated  
within end caps 822 and 824 and the whole tubular assembly  
20 is tightly sealed into end caps 822, 824 against hydrogen  
leakage by an insulating plastic sealant 844. Electrical  
connections are shown schematically at 846.

The purpose of the external wound filament 842 is to exert  
25 an evenly distributed clamping pressure on cathode member  
818 to hold anode 814 and cathode 818 in tight, intimate  
engagement with electrolytic member 816 and to withstand  
swelling of electrolytic member 816 caused by generation of  
water therein. Accordingly, the material employed for  
30 filament 842 should be of relative high tensile strength  
and it should also be resistant to the corrosion that can  
occur in a damp, warm or even hot oxidizing atmosphere.  
Accordingly, metal wires are not ideal and, if used should  
be plastic coated. A preferred material is a plastic-  
35 coated, glass fiber filament, for example a TEFLON  
(DuPont's trademark for polytetrafluoroethylene)-coated,  
glass-fiber sewing thread. This filament has good tensile  
strength, is highly resistant to corrosion or other  
chemical attack, even at elevated temperatures, and the use  
40 of TEFLON gives it a hydrophobic, water-shedding character,  
facilitating the discharge of water from the fuel cell.

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5 Filament 842 is wound with a pitch providing spacing  
between individual windings for the access of oxygen to the  
cathode, and for egress of water, or water vapor,  
therefrom. Preferably, this pitch is such that the spacing  
10 is between half and twice the thickness of an individual  
winding, with cross-layering of multiple windings being  
possible, so long as adequate gas-access and water release  
is provided.

Fuel cells such as that depicted in Figure 1 can be  
15 assembled by winding flexible woven carbon cloth sheets  
around a rigid porous plastic tube with a film of NAFION  
(trademark) electrolyte inserted between the carbon cloth  
layer which will provide the fuel cell's cathode 818 and, if  
necessary, the composite tubular assembly is then cut to  
20 length, and sealed into end caps 822, 824.

In a modified prior art embodiment, a wound casing  
material, such as the TEFLON-coated, glass fiber filament  
referred to hereinabove, to hold electrode members in  
25 intimate contact with an electrolyte can be extended to a  
stacked plate, fuel cell assembly in which multiple flat  
layered cells lie one on top of another as disclosed, for  
example in Aldhart and as shown in Figure 2. In the  
embodiment of Figure 2, flat laminar fuel cell assemblies  
30 860, each comprising a proton exchange membrane sandwiched  
between cathodic and anodic electrodes are interspersed  
between gas-distribution plates 862. External filament  
windings 864 (shown with exaggerated spacing for clarity)  
can be tightened around the assembly, optionally in  
35 multiple layers, which may be wound with opposing pitch  
angles to traverse one another, provided that sufficient  
openings remain for adequate air or oxygen access to the  
distribution plates 862.

40 Though providing useful advances in the art, these filament  
wound embodiments of fuel cell suffer still have a number  
of drawbacks. Both embodiments are unduly complex to  
manufacture. The tubular embodiment of Figure 1 can be

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5 lightweight and portable but is subject to current  
collection difficulties owing to the necessity of passing  
current through end connectors, while the Figure 2  
embodiment suffers all the drawbacks of weight and expense  
inherent in stacked plate fuel cell assemblies. These  
10 problems are solved by the present invention, some  
embodiments of which are illustrated in Figures 3-15.

One embodiment of the inventive hydrogen fuel cell is shown  
in Figures 3(a) through 11. Referring to Figure 3(a), in  
15 accordance with this embodiment of the hydrogen fuel cell,  
a first hollow member 910 is provided defining an interior  
space and having a peripheral surface. The first hollow  
member 910 receives a hydrogen containing gas and has a  
construction effective for passing the hydrogen containing  
20 gas from the interior space to the peripheral surface. The  
first hollow member 910 may comprise a porous tube, in  
which case the hydrogen containing gas passes through the  
pores in the porous tube from the interior space to the  
peripheral surface.

25 Alternatively, as shown in Figures 3(a), 3(b), the first  
hollow member 910 may comprise a hollow tube having  
through-holes 912 for passing the hydrogen containing gas  
from the interior space to the peripheral surface. Grooves  
30 914 can be disposed on the peripheral surface in  
communication with the through-holes 912 for facilitating  
dispersal of the hydrogen containing gas.

As shown in Figures 4(a) and 4(b), a first conductive  
35 winding 916 is wound around the peripheral surface of the  
first hollow member 910 to form an anode. The first  
conductive winding 916 includes a catalyst effective for  
decomposing hydrogen molecules in the hydrogen containing  
gas into active atomic hydrogen. The first conductive  
40 winding 916 may be made from titanium wire having a  
platinum coating or a platinum plating. The first  
conductive winding 916 forms an anode of the hydrogen fuel  
cell.

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5 As shown in Figures 5(a) and 5(b), a proton-exchange  
electrolyte member 918 is disposed around the first  
conductive winding 916 to transport protons. The  
electrolyte member 918 preferably comprises a NAFION  
10 (trademark) perfluorosulfonic acid polymer (also called an  
ionomer) film tube which is shrunk around the first  
conductive winding 916 so that the anode of the hydrogen  
fuel cell is in intimate contact with the electrolyte  
member 918. Such shrink-fitting can be effected by using  
the marked ability of NAFION (trademark) polymer membrane  
15 to swell when wetted. A wet polymer sleeve electrolyte  
member 918 is fitted over a first conductive winding 918  
sized to be a close fit when the electrolyte member is wet.  
Thus enveloping first conductive winding 916, electrolyte  
member 918 is dried to shrink it tightly on to first  
20 conductive winding 916, in a state of considerable tension.

As shown in Figures 6(a) and 6(b), a cathode is formed by  
winding a second conductive winding 920 around the  
electrolyte member 918. The second conductive winding 920  
25 also has catalytic properties effective for decomposing  
oxygen molecules in an oxygen containing gas into active  
oxygen atoms. The second conductive winding 920 may  
comprise a titanium wire having a platinum coating or a  
platinum plating. As is well known in the catalyst arts,  
30 rare metal catalyst such as platinum, palladium or their  
equivalents are more effective in a finely divided state.  
The present invention also contemplates provision of such  
finely divided catalyst, preferably more or less evenly  
distributed, across the gas-permeating outer surfaces of  
35 electrolyte member 918. While such catalytic means may be  
integral with the windings 916 and 920, for example as the  
above-described coating, it may alternatively be separately  
introduced into the interstices of the windings 916 and  
920. After the cathode is formed by winding a second  
40 conductive winding 920 around the electrolyte member 918,  
the electrolyte member 918 is expanded (such as by swelling  
due to the addition of water to the electrolyte member  
918).

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5 Referring to Figures 7(a) and 7(b), a second hollow member  
922 is provided for containing the first hollow member 910,  
the anode (first conductive winding 916), the electrolyte  
member 918 and the cathode (second conductive winding 920).  
The second hollow member 922 receives the oxygen containing  
10 gas, which may be ambient air, air enriched with O<sub>2</sub>, or pure  
O<sub>2</sub>, or the like.

As shown in Figure 8, a male end cap 924 and a female end  
cap 926 are provided for sealing the inventive hydrogen  
15 fuel cell. The ends of the anode and the cathode (first  
conductive winding 916 and second conductive winding 920)  
terminate in wire ends 928 which are received into  
connection ports 930 of the male end cap 924 and the female  
end cap 926. The connection ports 930 of the male end cap  
20 924 provide electrical connection between the wire ends 928  
of the anode and cathode and respective electrical  
connection terminals 932. The connection ports 930 of the  
female end cap 926 provide electrical connection between  
the wire ends 928 of the anode and the cathode, and include  
25 respective electrical connection sockets 934. The  
electrical connection sockets 934 can receive the  
electrical connection terminals 932 of the male end cap 924  
of another hydrogen fuel cell when connected (as shown in  
Figure 9), if end-to-end fuel cell connection is desired.  
30 Alternatively sockets 934 and terminals 932 may be capped  
or may be plugged to a connector block or strip, or the  
like, designed to accommodate multiple such cells.

Hydrogen gas is introduced through a hydrogen gas port 936  
35 of the male end cap 924 and enters into the interior space  
of the first hollow member 910. The hydrogen port 936 of  
the male end cap 924 terminates at a male fitting 938 which  
is received by a female receptacle 940 of the hydrogen port  
936 of the female end cap 926. Oxygen containing gas is  
40 introduced into the inventive hydrogen fuel cell through an  
oxygen port 942 on the male and female end caps 924, 926.  
The oxygen port 942 on the male end cap 924 terminates in  
an oxygen port fitting 944 which is received by a female

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5 receptacle 946 of the female end cap 926.

The modified male end cap 924 shown in Figure 8(b) provides for series connection between fuel cells by reversing the polarity of connection terminals 932 versus connection  
10 ports 930 with a crossover 933. Crossover 933 connects a radially inner connection port 930, mating with a negative polarity wire 928 on one cell, to a radially outer connection terminal 932, mating with a positive polarity connection socket 934 on an adjacent cell. Series  
15 connection will usually be desirable for higher voltage output, since fuel cells according to the invention can generate very substantial currents but yield only modest individual voltages, perhaps 0.6 or 0.7 volts.

20 As shown in Figure 9, the interfittability of the end caps, coupled with the fact that all joints to be sealed against hydrogen leakage are at the opposed ends of each cell enables the cells to be assembled end-to-end in modular fashion. When two hydrogen fuel cells are thus joined  
25 together, the male end cap 924 of the first hydrogen fuel cell mates with the female end cap 926 of the second hydrogen fuel cell so that the anode and cathode connection terminals 932 plug into the respective connection sockets 934 of the female end cap 926 for electrical connection  
30 between the anode and cathode of the respective hydrogen fuel cells.

The male fitting 938 of the male end cap 924 is received by the female receptacle 940 of the female end cap 926, and  
35 the oxygen port fitting 944 of the male end cap 924 is received by the female receptacle 946 of the female end cap 926 thus joining the first hydrogen fuel cell to the second hydrogen fuel cell. Multiple hydrogen fuel cells may be connected in a similar manner. The hydrogen fuel cells may  
40 then be clamped together or otherwise secured (not shown). Joints between adjacent cells can readily be sealed with a suitable polymeric sealant. Because of the configuration of the inventive fuel cell, expansion of electrolytic



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5 member 918, as it absorbs by-product water, does not subject the cell's seals to separating forces.

As shown in Figure 10, the first conductive winding 916 (anode) is in close intimate contact with the NAFION (trademark) electrolyte member 918. Also, the second conductive winding 920 (cathode) is in close intimate contact with the NAFION (trademark) electrolyte member 918. During operation of the inventive hydrogen fuel cell, hydrogen gas is supplied to the interior space of the first hollow member 910 and passes through the first hollow member 910 to the peripheral surface thereof. Hydrogen molecules here come in contact with the platinum catalyst 949 coated on the first conductive winding 916 and decompose into hydrogen atoms which then have their electrons stripped, resulting in the formation of protons which are transported through the NAFION (trademark) electrolyte member 918 to the cathode constituted by the second conductive winding 920. Oxygen containing gas introduced into the second hollow member 922 comes into contact with the platinum catalyst 949 coated on the second conductive winding 920. The oxygen molecules are broken down into oxygen atoms that accept electrons while reacting with protons reaching the cathode side of the electrolyte member, and thus form water. During the operation of the inventive hydrogen fuel cell, electrons are driven to flow in the opposite direction to proton travel providing an electrical current, thereby enabling productive use of the energy released through the operation of the inventive hydrogen fuel cell.

35 Figure 10 further shows, in a schematic way, how electrolytic member 918 expands as it becomes wet in use to fill the spaces between windings 916 and 920 and to become tightly packed therebetween. This arrangement, as will be apparent from considering Figure 10, provides some means for taking up the expansion of electrolytic member 918 as it absorbs moisture without imposing disruptive forces on the cell structure that might, in other constructions,

5     separate cell elements causing gas leakage.

Arrow 962 in Figure 10, shows a direction of hydrogen access to the electrolytic member 918 between two windings 916 which, if necessary for gas access, can be spaced  
10     apart, with a maximum spacing between windings 916 or 920 of about one quarter the diameter of an individual winding. However, for a gas with the migratory powers of hydrogen, the combination of a normal tight-packing of windings 916 and a modest gas pressure of a few pounds per square inch  
15     can be adequate to permit hydrogen to access the electrolytic member 918.

Similarly, oxygen can be supplied in the form of compressed air in the direction of arrow 960, using somewhat higher  
20     pressures of about 10 to 20 psig. With the structure shown, in order to gain access to the electrolytic member 918 the gases must pass through a closely confining channel between individual windings 916 and 920 where they are exposed to the catalyzing action of surface coating 949 on  
25     windings 916 and 920, over an extended area, thus enhancing dissociation into atomic hydrogen or oxygen.

Figure 10(a) shows an alternative construction of fuel cell having windings 916 or 920 designed further to enhance  
30     catalytic activity. Here, windings 916 or 920 have a square or rectangular cross-section further to increase the extent of the channel through which the migrating gases travel to access electrolytic member 918. In addition the windings are subjected to surface treatment to increase the  
35     surface area of catalyst. The surface treatment can be any one of various forms of mechanical actions effected for example with a diamond die, such as roughening, scoring or grooving. In Figure 10(a) transverse angled grooves are shown which serve to maintain a gas access passage between  
40     a gas windings while extending the distance traveled by gases passing over the catalyst surface to improve the catalytic action. Surface roughening or other surface configurations can be employed in place of the grooving.

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5 Because fuel cells of the type disclosed herein develop  
rather modest voltages of about 0.6 or 0.7 volts, it is  
important that withdrawal of current from the cell be  
effected with a very low impedance current collection  
system. The novel winding structures disclosed herein  
10 facilitate very low resistance current collection and  
contact between adjacent roughened windings 916 as shown in  
Figure 10(a), is a further safeguard, helping keep  
resistances low. By employing catalyst-coated windings, as  
disclosed herein, the invention ensures that there is a  
15 catalytical active zone physically outside the boundaries  
of the electrolytic member 918, the wet environment of  
which may tend to clog or smother the activity of  
conventional deposits or surface coatings of finely divided  
catalyst particles on the membrane itself. Clearly some  
20 catalytic activity may occur on the outer surfaces of  
winding 916 and 920 remote from electrolytic member 918 in  
a pre-reactivation process, or effecting dissociation of at  
least a small percentage of molecules before the membrane  
918 is encountered.

25 Figure 11 shows an alternative construction of the  
inventive hydrogen fuel cell. In this case, the male end  
cap has a threaded male fitting 938 that screws into a  
threaded female receptacle 940 of the female end cap 426 of  
another similarly constructed hydrogen fuel cell. The wire  
30 ends 928 of the anode and cathode exit through the second  
hollow member 922. The oxygen port fitting 944 is threaded  
for connection with an oxygen gas supply hose (not shown).  
The oxygen port fitting 944 is disposed on the second  
35 hollow member 922, so that the threaded male fitting 938 of  
a first hydrogen fuel cell can be screwed into the threaded  
female receptacle 940 of a second hydrogen fuel cell.  
Multiple hydrogen fuel cells can be easily connected  
together in this manner.

40 Figures 12(a) through 13(b) show a multiple fuel cell  
assembly in accordance with another aspect of the present  
invention. The multiple fuel cell assembly allows a number

5 of individual fuel cells (such as those having a  
construction as described herein) to share a single  
replaceable hydrogen gas supply tank. Figures 12(a) and  
12(b) are a top plan view and a bottom plan view,  
respectively, of the multiple fuel cell assembly. Figure  
10 13(a) is a side plan view of an individual fuel cell 950,  
and Figure 13(b) is a side plan view of the replaceable  
hydrogen gas supply tank. A plurality of individual fuel  
cells 948 is disposed around a central hydrogen gas supply  
tank 950. Hydrogen gas is received by each individual fuel  
15 cell 948 through a corresponding gas supply line 952. The  
hydrogen gas supply tank 950 has a screw fitting 958 (shown  
in Figure 13(b)) that is screwed into a distribution cap  
956. During operation, hydrogen gas from the hydrogen gas  
supply tank 950 is distributed to each individual fuel cell  
20 948. The individual fuel cells 948 are contained within  
common containing walls 954, between which oxygen  
containing gas flows for use by the fuel cells 948 in the  
generation of electricity. Alternatively, each individual  
fuel cell 948 may be contained within a corresponding  
25 containing structure, or open to the ambient air. The  
individual fuel cells 948 can be dimensioned to accommodate  
a standard gas cylinder, thus obviating the need for a  
specially manufactured hydrogen supply tank. The structure  
shown in which fuel cells 948 surround or enclose a  
30 hydrogen canister 950 permit transfer of heat from cells  
948 to canister 950. This heat can be utilized to cause  
hydrogen to flow, or to increase the hydrogen flow from  
supply tank 950 and is particularly beneficial in  
maintaining hydrogen flow from a hydride hydrogen source,  
35 especially under low temperature ambient conditions.

As an example, a configuration of the multiple fuel cell  
assembly may include 16 individual fuel cells 948 each  
having a diameter of four inches and a length of 24 inches  
40 for an electricity producing active area of about two  
square feet per cell. The total electricity producing  
active area in this example configuration is thus 32 square  
feet. The hydrogen gas supply tank 950 may have a volume

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5 of 2.5 cubic feet. The containing walls 954 define a space  
having an inner diameter of about 22 inches and an outer  
diameter of about 32 inches so that the overall size of  
this example of a multiple fuel cell assembly has a 32-inch  
diameter and a 24-inch length. It is estimated that such  
10 an assembly may, when operated at high or optimal  
efficiency, provide in excess of 10,000 watts of power.

Figures 12(c) and 12(d) show an alternative hydrogen  
delivery distribution system in which fuel cells 948 are  
15 connected in series so that hydrogen can be supplied from  
one to another down a pressure gradient. Here two radial  
hydrogen supply lines 970 extend from supply tank 950 to  
adjacent cells 948. Cells 948 are series interconnected  
top and bottom, in staggered manner, by links 972,  
20 alternately at the tops and bottoms of adjacent pairs of  
cells so that hydrogen passes up one cell and down the  
next. As shown here, hydrogen is fed from both ends of the  
series of cells 948, in two pressure gradients. If a  
single gradient is preferred, hydrogen may be fed to one  
25 end only through a single radial supply line 970.

#### Fluid Management

If desired, supplemental water, heat and gas circulation  
systems can be provided to service individual ones of the  
30 cells described herein, or preferably to service an array  
of such cells when assembled into a high power, light  
weight battery. A preferred such system, used to withdraw  
by-product moisture or water from the cell which can  
comprise a fan and recirculating means to withdraw air or  
35 oxygen from the cathode side of the cell. Preferred  
embodiments recirculate, or simply circulate, either air  
under fan pressure or compressed air in an enclosed system.  
Where feasible, subject to the intended operating  
environment of the fuel cell, a few atmospheres of  
40 compressed air may be desirable to improve cell efficiency.

A desirable or required operating condition of the type of  
fuel cell described herein, when employing a wet-operating

5 membrane, is that the anode, hydrogen-receiving side of the  
cell be kept moist. Often moisture is entrained in the  
hydrogen flow at the hydrogen source, especially if a  
hydride source is used. However, supplemental moisturizing  
10 of the hydrogen flow may be desirable and water for this  
purpose can be recovered from the cathode ventilating means  
described above.

Such fluid handling systems can be incorporated in a cell  
bank in the manner shown schematically in Figure 13(c). A  
15 cathode-side air or water pump 980 moves air over the  
cathodes of a bank of cells 948 withdrawing moisture or  
water therefrom, and cooling them. Output of pump 980  
passes to a water extractor 982 where water is separated  
and passes to anode humidifier 984. Dried air from water  
20 extractor 982 can be recirculated. Hydrogen pump 986 moves  
hydrogen through anode humidifier 984 to moisten it and  
delivers hydrogen to the anodes. With adequate air  
circulation, cooling is not necessary, but if desired, a  
heat extractor can be included in the air-water circuit.

25

#### Self-contained, renewable power source

Referring to Figure 14, a fuel cell such as that shown in  
Fig. 13 can be adapted to become a self-contained,  
renewable power source by receiving a screw-in hydrogen  
30 cylinder 990 into the cell, to be substantially contained  
therewithin. As shown, end plug 522 is modified to receive  
a cylinder 990 as a close fit, while end cap 520 is  
supplied with a screw fitting 992 to receive the hydrogen  
cylinder 990's nozzle 994. An interior liner 996 defines  
35 an annular hydrogen chamber 998 which admits nozzle 994  
through a snap valve 999.

#### Manufacture of Figures 3(a) through 11 embodiments

40 The hydrogen fuel cell shown in Figures 3(a) through 11 can  
be easily manufactured utilizing methods such, for example,  
as the inventive manufacturing methods described herein  
which are adaptable to high volume mass manufacturing  
techniques. A first hollow member 910 is provided defining

5 an interior space and having a peripheral surface. The first hollow member 910 is for receiving a hydrogen containing gas and is effective for passing the hydrogen containing gas from the interior space to the peripheral surface (Figure 3(a)). A first conductive winding 916 is  
10 wound around the first hollow member 910 to form an anode (Figure 4(a)). The first conductive winding 910 has a catalyst effective for decomposing hydrogen molecules from the hydrogen containing gas into  $H^+$  ions (Figure 10). An electrolyte member 918 is disposed around the anode.  
15 Preferably, the electrolyte member 918 comprises a tube of NAFION (trademark) film which is shrunk around the first conductive winding 916 (Figure 5(a)). A second conductive winding 920 is wound around the electrolyte member 918 to form a cathode. The second conductive winding 920 has a  
20 catalyst effective for decomposing oxygen molecules in an oxygen containing gas into oxygen atoms. After the second conductive winding 920 is wound around the electrolyte member 918, the NAFION (trademark) film electrolyte member 918 is expanded by introducing water to swell the NAFION  
25 (trademark) film [Figure 6(a)]. A second hollow member 922 is disposed loosely around the second conductive winding 920 for containing the first hollow member 910, the anode (first conductive winding 916), the electrolyte member 918 and the cathode (second conductive winding 920). The  
30 second hollow member 922 receives the oxygen containing gas which is then decomposed by the catalyst formed on the second conductive winding 920 [Figure 7(a)]. Finally, a male end cap 924 and a female end cap 926 are installed to complete the hydrogen fuel cell (Figure 26). A plurality  
35 of thus formed hydrogen fuel cells are joined together by mating the male end cap 924 of a first hydrogen fuel cell with the female end cap 926 of a second hydrogen fuel cell (Figure 9 and Figure 11).

#### 40 Some uses and advantages

Their self-contained, free-standing structure affords the tubular fuel cells of the invention many options for packing or assembling into batteries or arrays that are not

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5 possible with a fuel cell stack. In one example of a  
simple, practical array, useful for a field soldier, or  
other field operative, three tubular cells, each 2 inches  
(about 5 cm.) in diameter and 7 inches (about 18 cm.) in  
length can be mounted vertically onto a 9 inch (about 23  
10 cm.) wide belt wrapped around a soldier's waist. These  
three light-weight cells, preferably each weighing less  
than one pound (453 gm.), each contain about 30 square  
inches (193 sq. cm.) of active surface. Referencing the  
data reported in Figure 1 of Wilson et al., supra, page 16,  
15 a theoretical output of 1.5 amps/cm<sup>2</sup> at 0.6 volts is  
obtainable. Accordingly, if constructed as taught by  
Wilson et al., such a package of three cells will produce  
520 watts, a margin of power of almost two over a current  
U.S. Army specification for portable electric power sources  
20 for soldiers of the future.

The tubular cells of this invention overcome problems  
caused by the high coefficient of dry-to-wet expansion of  
NAFION polymer, primarily through the radial strength of  
25 extremely light weight carbon fiber sleeves having, in the  
fibers, tensile strength greater than steel. Moisture-  
absorbing electrolyte expansion exerts very little pressure  
on the seals of tubular cells, which as taught herein, are  
located at the joints at the ends of the cells.  
30 Importantly, in contrast to the multiple laminations that  
must be sealed and gasketed in stacked flat cells, there  
are only two seals to be made in each tubular cell, at the  
cell ends around the substantially circular ends of its  
multiple concentric tubular members. Structural stability  
35 is enhanced by using wound electrode members the windings  
of which can advantageously be heavy gauge conductor wire  
rated to remove the large currents generated with a minimum  
of impedance losses. The heavier the gauge, the greater  
the structural strength. Suitable end seals can be made  
40 through the use of cast resin in relatively large cross-  
sections or even by pressure molding plastic polymer to the  
ends of each cell.



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5 Unlike compressed flat cell stacks, tubular fuel cells can  
also be spatially separated, reducing heat build up and  
thermal management requirements. Water management  
requirements are also reduced because air can be circulated  
over substantially the entire cathode area to move water  
10 continuously away from it, using natural or forced  
convection.

Referring now to the embodiment of Figs. 15(a)-(f) there is  
shown a composite structure of fuel cell having a tapered  
15 tubular configuration with a taper along the tube which is  
here selected to be of the order of 1%. This cell  
incorporates many of the features of the foregoing  
embodiments, in combination.

20 The interfitting, nested, tapered shape of each tubular,  
sleeve-like cell members facilitates tight assembly of the  
various cell layers into intimate contact, each with its  
neighbor, so each electrolyte surfaces is pressed into  
intimate contact with a respective electrode throughout the  
25 electrode area, with a minimum of zones of poor, or  
unconstrained contact. The taper translates lengthwise  
stresses, imposed during manufacturing into lateral or  
radial compressive forces packing the nested layers  
together and permits lengthwise assembly of closely  
30 dimensioned interfitting layers.

The embodiment shown in Figs. 15(a)-(f) preferably employs  
inner and outer tapered-helix wound current collectors of  
sufficiently robust construction to constitute load-bearing  
35 formers. Also of note is the use of separately fabricated  
catalyst layers pressed onto either side of an electrolytic  
proton exchange membrane, sandwiching it, and the use of  
separately fabricated gas diffusion layers or members to  
manage distribution of oxygen and hydrogen to the catalyst  
40 and membrane layers.

The multi-layer construction of the cell is most readily  
apparent from the enlarged sectional view of Figure 15(f).

5 A polymer exchange membrane electrolytic member 1110 is disposed as a central layer. Reading down Figure 15(f), from electrolytic member 1110, in a direction inwardly toward the center of the fuel cell, the layers comprise anodic catalyst layer 1112, anode gas diffusion layer 1114, 10 an anode collection layer 1116 and an optional inner housing member 1118.

Reading upwardly from electrolytic member 1110, in a direction outwardly, of the fuel cell, there is a cathodic 15 catalytic layer 1120, a cathode diffusion layer 1122, a cathode collector 1124 and an oxygen supply passage 1126, the latter being defined in an outer housing member 1128.

Catalyst layers 1112 and 1120 are porous so as to be freely 20 gas-pervious and support a finely divided catalyst, such as platinum in a conductive medium, for example carbon black. Cathode catalyst layer 1120 also exhibits substantial water vapor porosity for the removal of water vapor from the cathode side of the cell. The porous conductive catalyst 25 layers 1112 and 1120 are preferably thin coatings and provide a distinct gas-dissociation stage in intimate contact with electrochemically active electrolytic member 1110 to ionize the dissociated atoms promptly before they recombine into molecules. Catalyst layers 1112 and 1120 30 are fine-pored and have a very high effective surface area to divide the gas flow into fine microscopic or sub-microscopic streams, and to ensure that a high proportion of gas molecules contacts the catalyst surfaces to be dissociated into atoms. The surfaces of catalyst layers 35 1112 and 1120 may be thought of as intermeshing with that of electrolytic member 1110 to increase the apparent surface area.

Currently preferred embodiments of the invention, employing 40 the preferred materials recited herein, have a thickness in the range of about 0.002 to 0.007 inch, with an ultra-thin catalyst layer coating of the order of one millionth of an inch.

5 Gas diffusion layers 1114 and 1122 serve laterally to spread the flow of gases migrating to the interior electrolytic layers of the cell from between the windings of current collector layers 1126 and 1124, permitting a better distribution of gas over the whole surface area of  
10 the cells or of the boundaries between the active layers. Each current collector 1116 and 1124 and its associated diffusion layer 1114 or 1122, can be regarded as constituting a corresponding cell electrode, collector 1116 and diffusion layer 1114 constituting the anode, while  
15 collector 1124 and diffusion layer 1122 constitute the cathode.

Desirably, electrolytic member 1110 extends beyond the hydrogen-distributing anodic layers 1112 and 1114, for  
20 hydrogen leak prevention. As shown in Fig. 15(d), end plugs 1132-1134, which may be prefabricated, but are preferably cast in situ from a non-conductive, hydrogen sealing resin or polymer, close the ends of the cell and provide hydrogen seals. Preferably the ends at least of  
25 electrolytic member 1110, anode catalyst layer 1112 and anode gas diffusion layer 1114 are embedded in the end plugs 1132 and 1134.

Current collectors 1116 and 1124 comprise open-form, or  
30 foraminated, structural conductive members, here shown as wire windings 1117 and 1125 respectively, each embedded in a conductive, gas-porous, structural matrix 1119 and 1127, respectively.

35 Windings 1117 and 1125 can be of any conductive material that has adequate tensile strength, load-bearing rigidity and can withstand the corrosive environment within the fuel cell. Metals such as titanium are preferred. A still more preferred winding 1117 and 1125 has a more complex  
40 structure and comprises titanium-clad copper wire which can be formed by drawing coaxial tubes of the two metals. Such a coated winding can have its titanium ends bared externally of the electrolyte environment to form copper

- 5 connectors which are preferable for outputting large currents at low voltages. Depending upon the cell's rating, windings 1117 and 1125 may be quite heavy gauge, up to perhaps one-sixteenth or one-eighth of an inch diameter. Besides windings, other forms of open-work, conductive  
10 former can be provided in tubular form, for example, braided or mesh or perforate structures or expanded metal such as expanded titanium available under the trademark DELKER.
- 15 With a view to reducing cell impedance, windings 1117 and 1125 may be in the form of coiled-coil filaments employing a fine gauge wire filament coiled to provide the winding, which coiled filament winding is coiled again around the fuel cell. Such a structure is intended to bring more  
20 current-collecting wire surface into closer contact with the surface of the electrolytic member 1110.
- Matrices 1119 and 1127 are preferably carbon black or other finely divided conductive material dispersed in a  
25 structural binder such as a substantially rigid porous resin or ionomer which is preferably hydrophilic to be conductive. Desirably, also a finely divided hydrophobic material such as polytetrafluoroethylene, for example, TEFLON (trademark, DuPont) is included in the matrix to  
30 shed water, especially on the cathode side of the cell. The matrix-embedded winding structure of current collectors 1116 and 1124 is lightweight yet has exceptional strength to contain expansion of electrolytic member 1110 and press the cell's electrodes into intimate engagement with it.
- 35 While described and shown as separate structural elements, modified embodiments of the invention are contemplated in which current collectors 1116 or 1124 are integral with diffusion layers 1114 or 1122, for example as shown  
40 schematically in Figure 15(e).

Optional inner housing member 1118 can provide structural support, if desired, for example, for a smaller embodiment

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- 5 of cell with a lower current rating having a smaller gauge, less robust winding 1116. Inner housing member 1118 can also optionally be adapted to provide other functions, such as hydrogen delivery enhancement.
- 10 One form of hydrogen delivery enhancement structure is embodied in grooves 1136 which constitute one or more continuous (tapered) helices delivering hydrogen to anode current collector 1116. Preferably, hydrogen is delivered to the electrolytic member 1118 so far as possible, along a
- 15 substantial pressure gradient, with the hydrogen moving in one direction through confined passageways so as to keep it moving and avoid stills or stagnancies that may impede cell performance.
- 20 Manufacture of tubular cells with wound electrodes
- A tubular cell having wound electrodes such as the tapered tubular cell shown in Figs. 33 (a)-(f), can be manufactured by the following method which is readily adaptable to mass production. A tapered steel mandrel is coated on its outer
- 25 surface with a release agent such as a polytetrafluoroethylene or a silicone. Over this surface is coated a slurry of finely divided platinum particles mixed with carbon black in an organic solvent dispersant. The slurry coating is dried and baked to form a sleeve on
- 30 the release surface of the conical mandrel, anode diffusion layer 1114.
- A tube of NAFION polymer is immersed in water to cause it to swell. It is then placed over the coated mandrel and
- 35 dried so that it shrinks tightly over the mandrel, forming electrolytic member 1110.
- Two half-tube metal molds, dimensioned to fit electrolytic member 1110, are coated with release agent then with a
- 40 platinum-carbon dispersion, as described above, and baked into place to form cathode diffusion layer 1122. The hot tubes and coating are pressed lengthwise onto the mandrel using its taper to compress the diffusion layers 1114, 1122

- 5 on to the polymer-film electrolytic member 1110 so that the catalyst layers transfer to it. The half tubes and mandrel are then removed lengthwise. If desired, or necessary, radial pressure can be exerted by known mechanical means.
- 10 Two titanium wire tapered tubes, carefully sized for nesting, one inside and one outside the assembled layers, are placed in tubular molds which are then filled with carbon black which has been treated according to the
- 15 directions of the Los Alamos Laboratory. The carbon black is molded under heat and pressure so as completely to envelop the titanium wire matrix, except for the ends which extend beyond the molded portion to provide current
- 20 connectors at each end of the tube. The products are suitable for use as anode and cathode current collectors 1116 and 1124.
- Final assembly of the composite tube is effected by placing the electrolyte tube 1110 with catalytic layers 1112 and 1120 over the smaller diffusion tube 1114 and then placing
- 25 the larger diffusion tube 1122 over the catalyst-covered electrolyte tube 1110. The nested tubes are pressed firmly together, lengthwise, with heat applied, if desired.
- Plastic end plates fitted with small gas tube fittings
- 30 such, for example, as shown in Figures 26(a), 26(b) and 11, are pressed into the inside of the center wire tube at one end and over the outside of the outside wire tube at the other end. A plastic air cover with entrance and exit tube fittings is placed over the end pieces.
- 35 Plastic sealant is then poured into the seal area adjoining each end piece to form sealed end plugs 1132 and 1134 and complete the assembly.
- 40 The above-described manufacturing steps can be included in a production assembly line which also includes test equipment for final testing of each fuel cell. Many of the operations can be carried out by robots as none of the

- 5 individual operations requires difficult manipulation.

The fuel cell embodiments of the invention described herein permit simplified fuel cell manufacture through elimination of the complicated sealing and gasketing required to build  
10 stacks of flat cells. The innovations described and disclosed herein provide novel fuel cells designed to achieve commercial reliability, that are commercially adaptable to mass production manufacturing techniques at a commercially acceptable price, and are ultra light weight.

15 In summary, the several embodiments of the invention disclosed herein provide great freedom of choice to an engineer in developing improved wet-membrane, room temperature-operative fuel cells, especially hydrogen fuel  
20 cells, by avoiding the constraints imposed in stacked fuel cell assemblies, where swelling of the electrolytic membranes induced by water synthesis in the cells acts in directions that tend to open gas seals designed to contain the gaseous fuel. Fuel leakage, and especially leakage of  
25 highly volatile, flammable gaseous hydrogen, with its attendant risks of fire and explosion, is an important problem to avoid. To maintain the seals in stacked, wet-membrane fuel cells, heavy weight cumbersome, expensive and restrictive mechanical structures have been used, prior to  
30 the present invention, such as the steel cover plates 24, manifold covers 26 and screws 28, that are used by Adlhart to bolt the fuel cell together and compress the stack (column 7, line 64 to column 8, line 3). Since each cell may have 10 or more laminations and stacks of only about  
35 seven cells may have hundreds of apertures to seal, reliability is also poor.

In contrast, the invention permits multiple fuel cells to be disposed freely in a variety of configurations,  
40 including in a side-by-side manner, enabling the peripheries of individual cells to be separately sealed by members or sealants that are not subjected to swelling forces generated in the ion-exchange electrolytic membrane.

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5 This separation of functions enables the problem of  
maintaining intimate contact between the electrode members  
and the swollen electrolytic membrane to be addressed by  
separately acting structural means such as the self-  
clamping tapered electrode members, and the wound filament  
10 described herein.

Gas ducting is also facilitated because, in the inventive  
embodiments, fuel and oxidizing gases do not have to be  
supplied through load-bearing distribution members, and can  
15 access the electrode surfaces through porous members which  
may also serve structural support functions, or through  
simple pipe-like ducts, or can be channeled by the  
electrodes themselves or, in the case of the cathodes may  
simply be exposed to an ambient atmosphere. Thus, much  
20 more open configurations are possible, yielding flexibility  
in the detailed design of means for supplying hydrogen and  
oxygen to the inventive fuel cell and for removing water  
therefrom.

25 Tubular and tapered tubular embodiments of fuel cell, such  
as those shown in Figs. 13 on, are particularly well  
adapted to function at relatively low, albeit elevated  
temperatures (circa 80-100°C), with wet-operating  
electrolytic membranes which are prone to substantial  
30 swelling in operation, by absorbing the swelling forces  
between concentric tubular members. Where the concentric  
tubular members comprise carbon fibers, derived for example  
from woven carbon cloth, exceptional tensile strength and  
conductivity is provided in a light weight structure.  
35 NAFION (trademark, DuPont), in the present state of the  
electrolytic membrane arts is a preferred material for the  
electrolytic member but will swell as much as 16% when  
wetted. As a fuel cell is repeatedly powered up and shut  
down during use, its electrolytic member undergoes repeated  
40 swelling and shrinkage. Moisture is generated in use. The  
cell dries out when shut down, and repeatedly heats up and  
cools down as it is used. Such continued cyclical  
expansion and contraction imposes enormous stresses on



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5 structural confining members of the cell, which are  
effectively accommodated by the tubular and tapered  
structures described and shown herein.

10 If and when available, electrolyte members that do not  
swell will be desirable for incorporation in fuel cell  
embodiments such as those shown in Figs. 1-12 to be  
conveniently available in extended, preferably flexible  
strips and rolls.

15 In turn, these innovations permit a wide variety of  
different structures and geometrical configurations to suit  
different operating requirements and design parameters,  
giving skilled workers great freedom of design choices, in  
adapting the invention to particular circumstances, as  
20 witnessed by the strip, tubular and conical cell  
embodiments described herein which can all be fabricated  
from lightweight, economical and adaptable carbon-fiber and  
polymeric materials, and which can also be configured in to  
flexible structures, giving manufacturers and users an  
25 additional range of possibilities.

While an illustrative embodiment of the invention has been  
described above, it is, of course, understood that various  
modifications will be apparent to those of ordinary skill  
30 in the art. Such modifications are within the spirit and  
scope of the invention, which is limited and defined only  
by the appended claims.

5    **Claims**

Claim 1. A wet-operating electrolyte, curved shape, oxygen-reduction fuel cell comprising gas-pervious, curved current-collecting electrodes shaped to mate one with another, gas-dissociating catalyst zones at each electrode and a proton transport electrolytic member constrained between the current collecting electrodes, the current-collecting electrodes are load-bearing structures acting to compress the electrolytic member characterized in that at least one of the electrodes includes a coiled winding acting to assist compress the electrolytic member.

Claim 2. A fuel cell according to claim 1 characterized by having a generally tubular shape with tubular components, each the electrode comprising concentric tubular coils, the electrolytic member being compressed between the tubular coil electrodes.

Claim 3. A fuel cell according to claim 2 characterized by comprising a porous gas diffusion layer, one for each current collector, to spread gas permeating the current collectors for uniform delivery to catalyst layers adjacent the electrolytic member.

Claim 4. A fuel cell according to claim 3 characterized in that the gas diffusion layers comprise carbon black in a porous conductive binder.

Claim 5. A fuel cell according to claim 1 characterized in that the catalyst zones comprise thin films of catalyst particles deposited one on each surface of the electrolytic member.

Claim 6. A fuel cell according to claim 1, 2 or 3 characterized in that each winding comprises a conductive winding having a platinum coating.

Claim 7. A hydrogen fuel cell characterized by being shaped to receive and embrace a hydrogen supply canister to

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- 5 provide a self-contained portable electricity generating unit.

Claim 8. A fuel cell according to claim 7 characterized by including the hydrogen supply canister, the hydrogen supply  
10 canister having a volume and being received into the fuel cell to an extent of at least one half of the volume.

Claim 9. A method of manufacturing a hydrogen fuel cell comprising a self-supporting shaped, layered electrode  
15 structure in which a solid-phase proton-transporting electrolyte is sandwiched between a porous anodic electrode and a porous cathodic electrode, characterized by comprising the steps of

- 20 a) coating a first, shaped self-supporting electrode with a curable, liquid-phase, proton-transporting electrolytic material to provide an electrolytic coating;
- b) curing the electrolytic coating to the solid phase;
- 25 c) assembling the coated electrode with a second, mating, shaped electrode to provide the layered structure;
- d) and assembling the electrode structure with a support base.

30

Claim 10. A method according to claim 9, comprising a further step of coating the first electrode with a catalyst-containing curable, liquid-phase proton-transporting material.

35

Claim 11. A method according to claim 10, characterized in that the curing step has two stages: a first, solvent-evaporation stage at a moderately elevated temperature, and a second purification or decontamination stage at a higher  
40 temperature.

Claim 12. A method of manufacturing a shaped, non-flat, layered fuel cell of the wet-electrolyte type, having fuel

- 5 cell components comprising current collecting electrodes  
and a wet-operating electrolytic member compressed between  
the electrodes, wherein oxygen is reduced by a combustible  
gas, the method comprising the steps of:
- 10 a) forming a first gas-pervious, load bearing,  
current collecting electrode to a first shape;
  - b) forming a second gas-pervious, load bearing,  
current collecting electrode to a second shape  
mateable with the first shape; and
  - 15 c) assembling the first and second current-  
collecting electrodes with the electrolytic  
member into a self-supporting structure;
- characterized in that each electrode comprises an open-work  
load-bearing metal structure.
- 20 **Claim 13.** A method according to claim 12 characterized in  
that the fuel cell components include gas diffusion members  
to spread reaction gases for uniform distribution to  
opposed surfaces of the electrolyte.
- 25 **Claim 14.** A method according to claim 12 or 13  
characterized in that the metal is titanium.
- Claim 15.** A method according to claim 12 or 13  
characterized in that the metal structure is selected from  
30 the group consisting of a coiled winding, expanded metal  
and metal braiding.
- Claim 16.** A method according to claim 12 or 13  
characterized in that one or more of the fuel cell  
35 components is shaped around a former.
- Claim 17.** A method according to claim 12 or 13  
characterized by comprising inserting plugs at the ends of  
the fuel cell to seal the fuel cell against loss of  
40 combustible gas.
- Claim 18.** A method of manufacturing a shaped, non-flat,  
layered fuel cell of the wet-electrolyte type, having fuel

- 5 cell components comprising current collecting electrodes  
and a wet-operating electrolytic member compressed between  
the electrodes, the method characterized by comprising the  
steps of:
- 10 a) forming a first gas-pervious, load bearing,  
current collecting wound titanium wire electrode  
to a coiled, tapered open-ended tube;
  - b) forming a second gas-pervious, load bearing,  
current collecting titanium wire electrode to a  
15 coiled tapered tube sized to receive the first  
electrode and to mateably clamp the electrolytic  
member between the electrodes; and
  - c) assembling the first and second current-  
collecting electrodes with the electrolytic  
20 member by inserting one component into another  
lengthwise;
  - d) pressing the components together lengthwise to  
compress the electrolytic member radially; and
  - e) plugging the tube endwise to seal the cell  
against loss of combustible gas.

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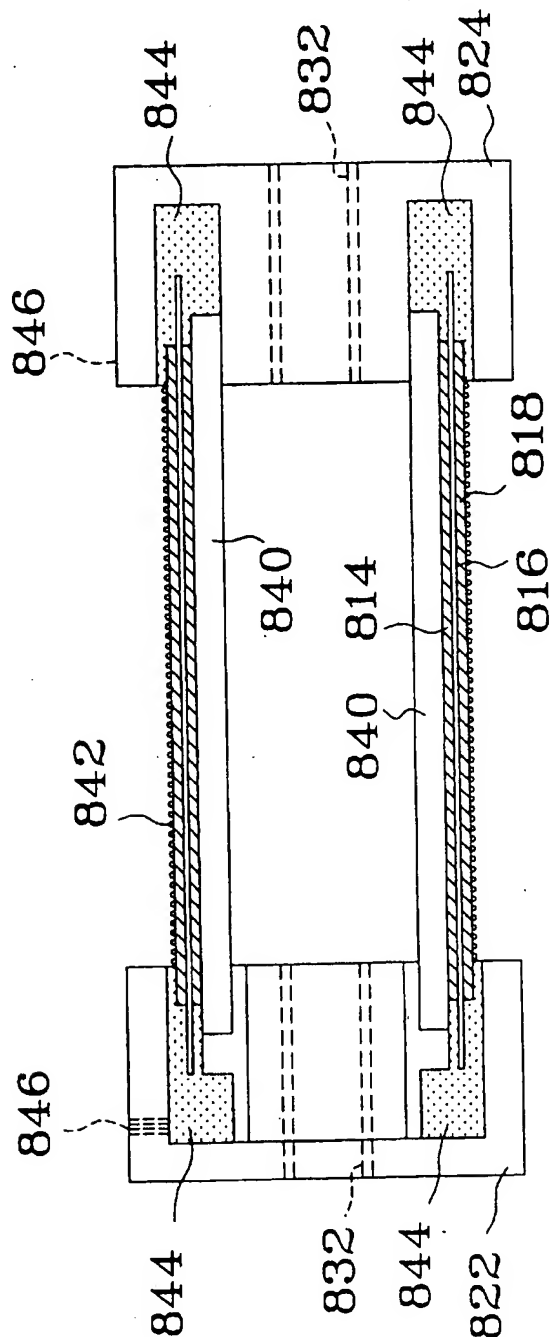


Figure 1

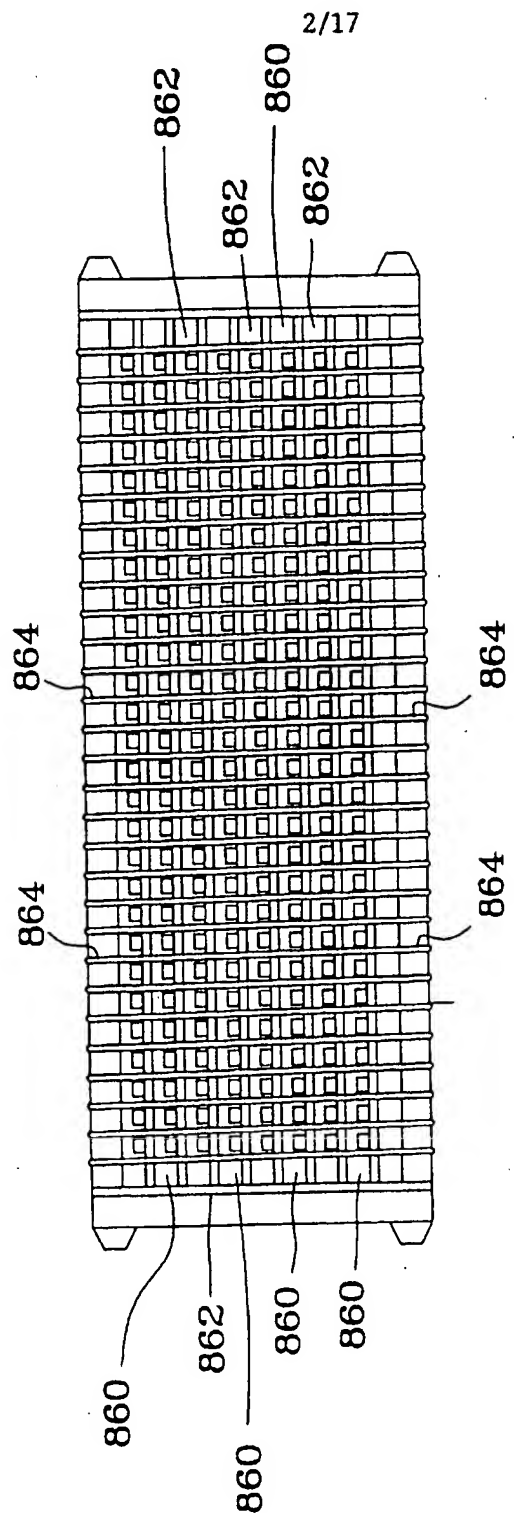
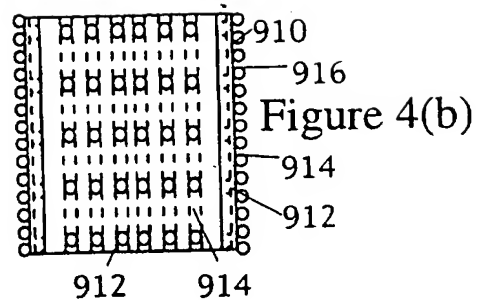
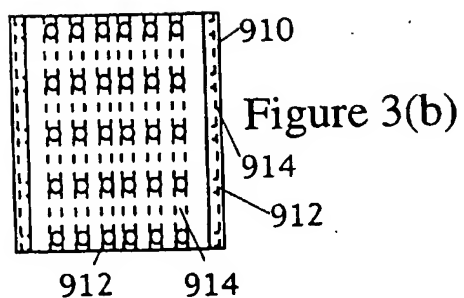
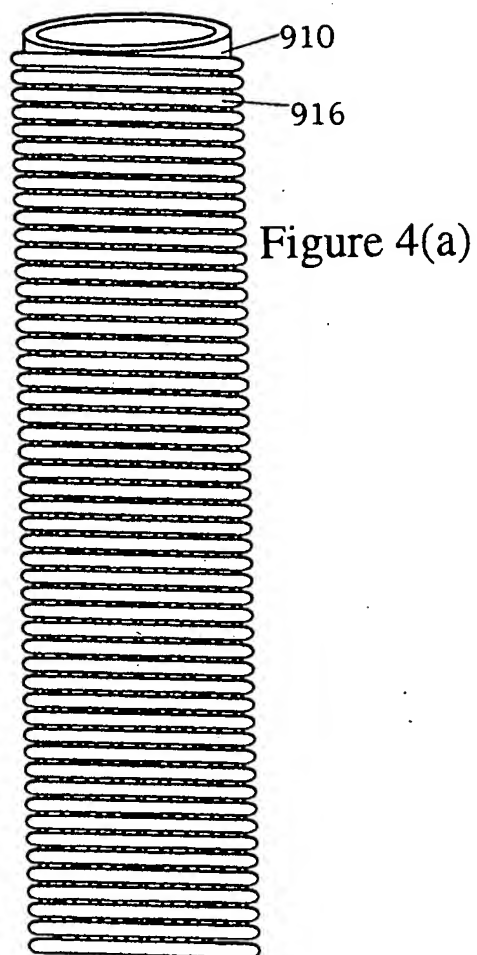
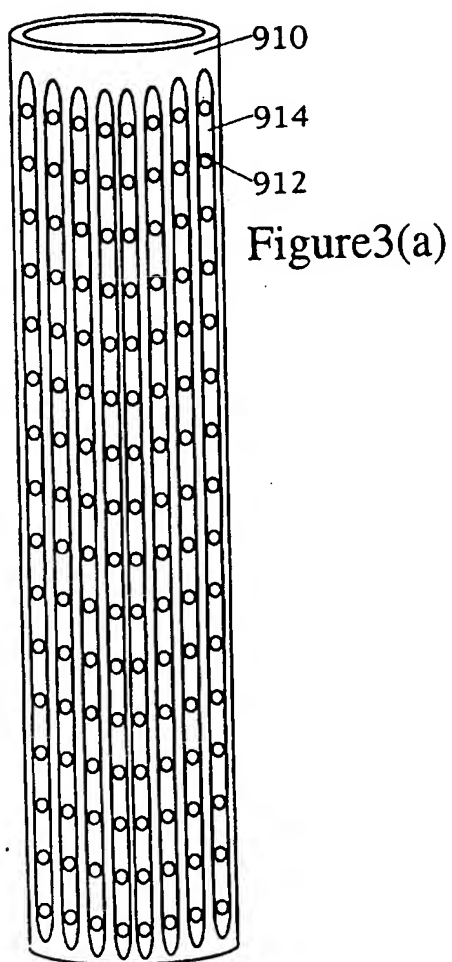


Figure 2

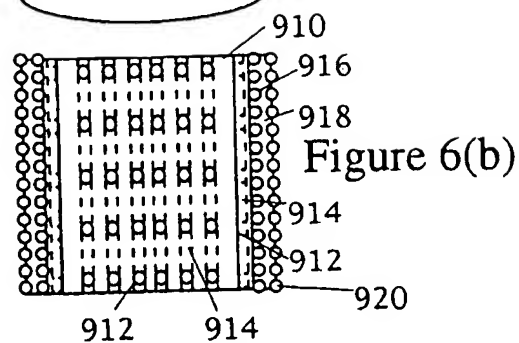
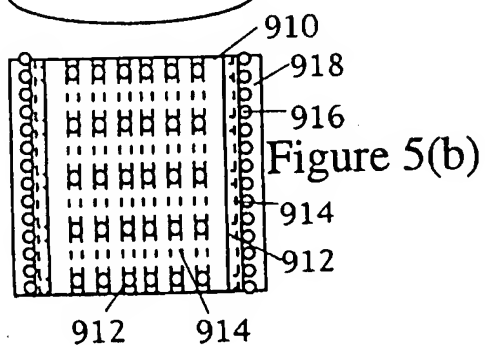
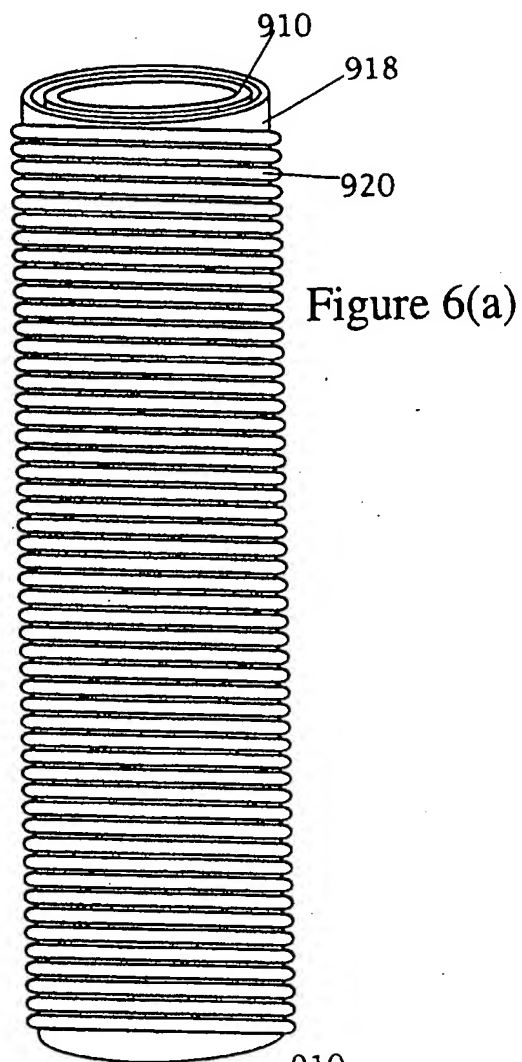
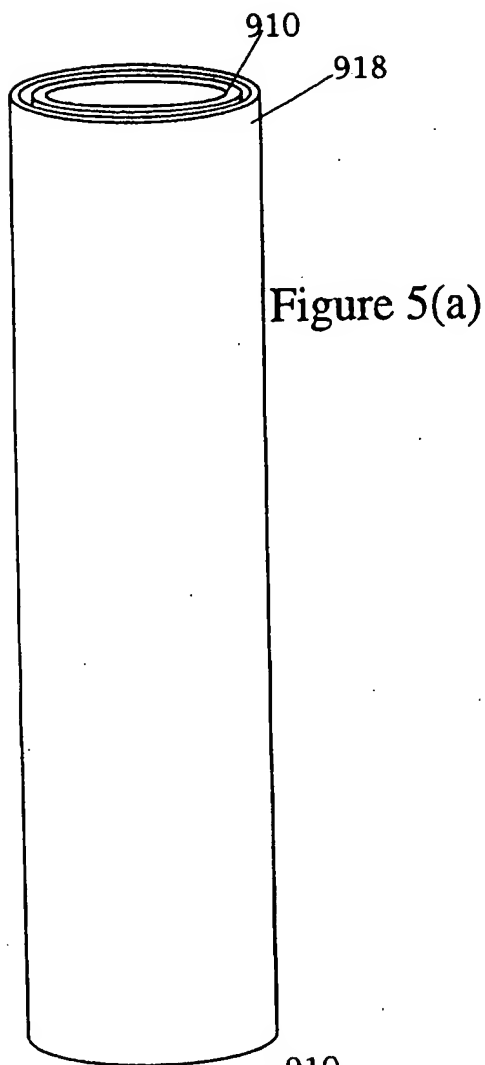
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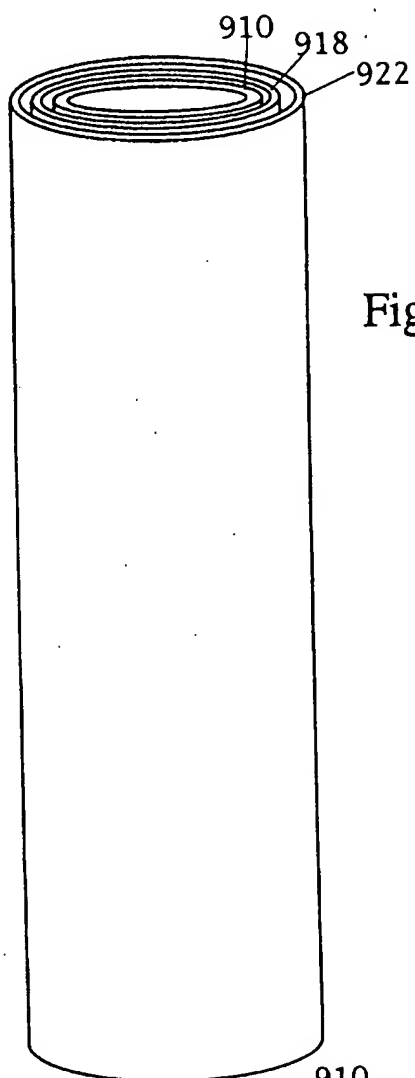


Figure 7(a)

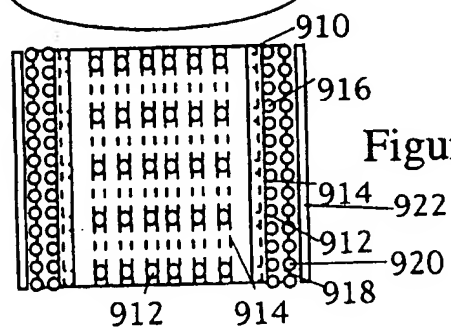


Figure 7(b)

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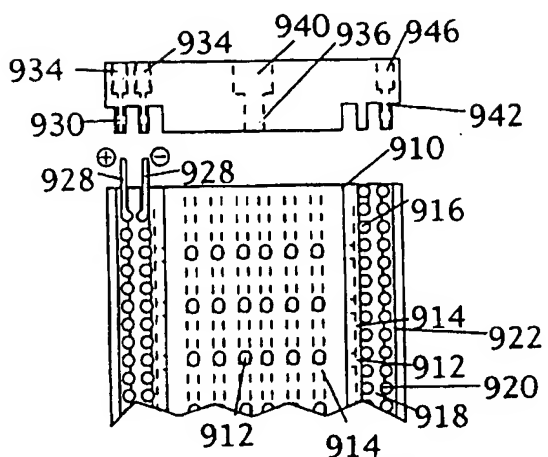


Figure 8(a)

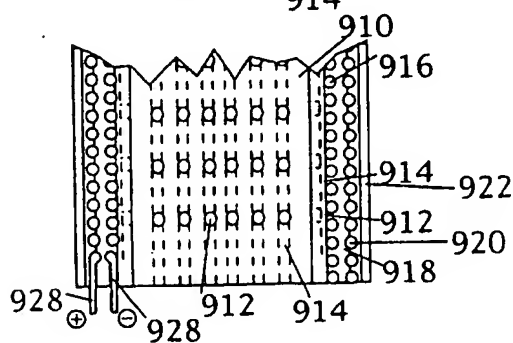


Figure 8(b)

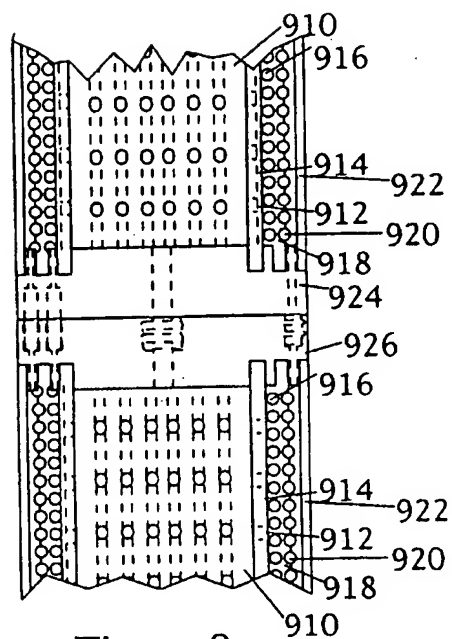
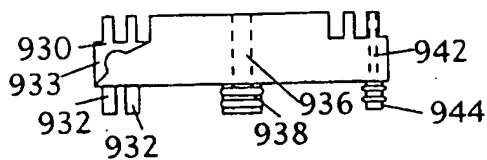


Figure 9



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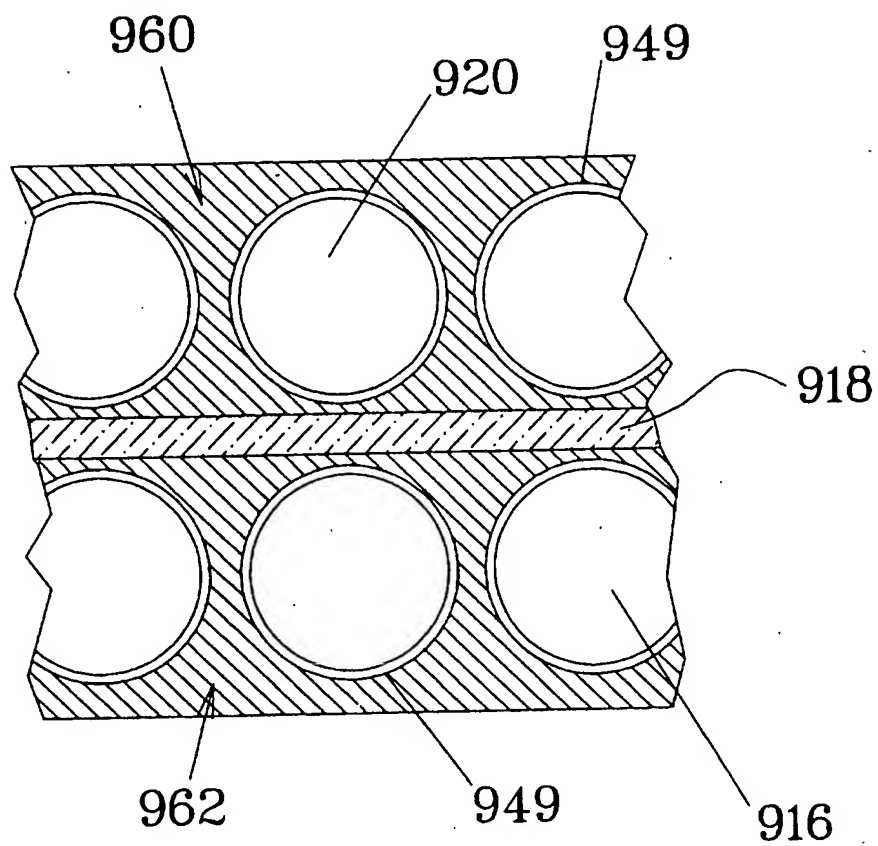


Figure 10

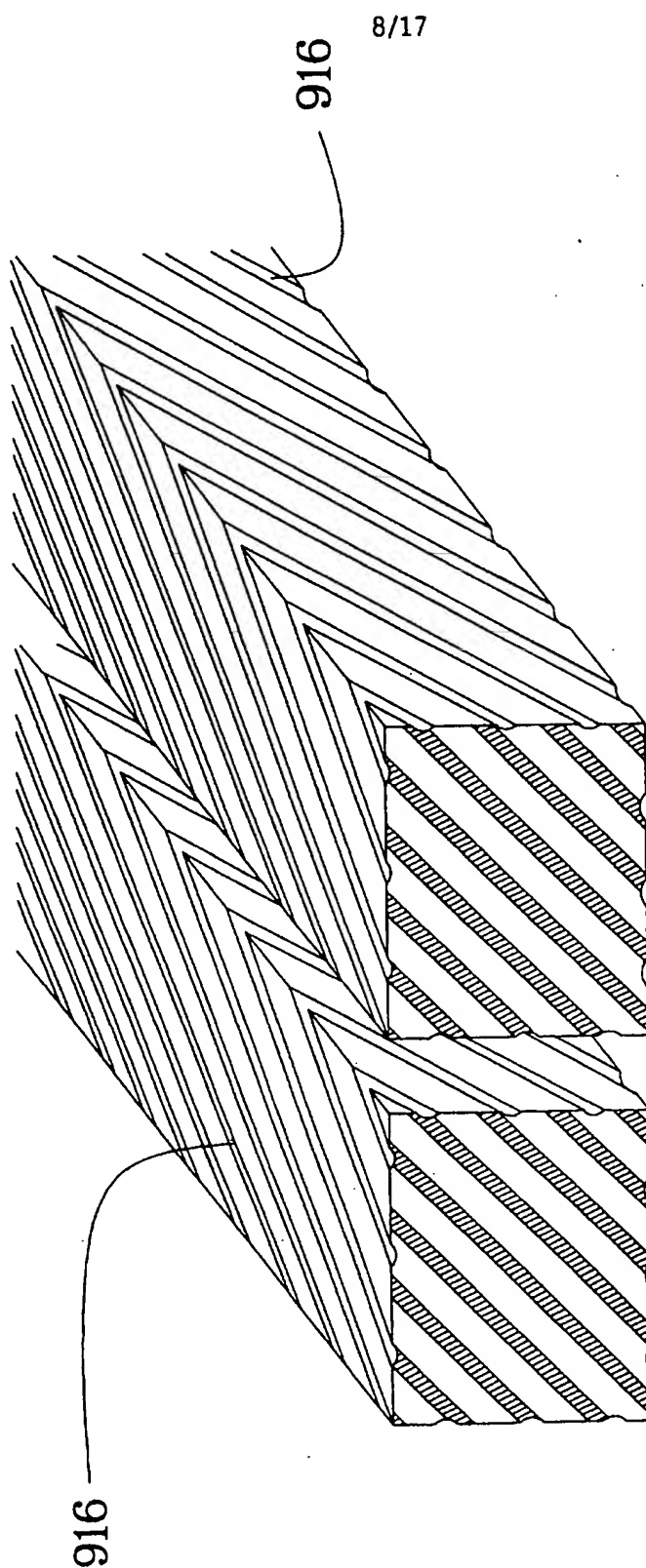


Figure 10(a)

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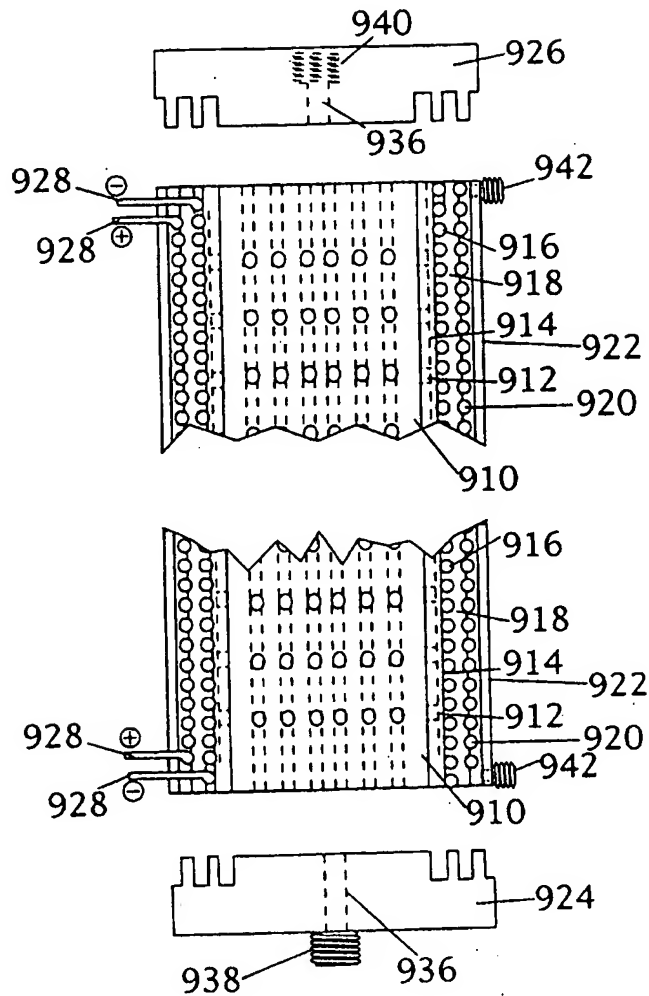


Figure 11

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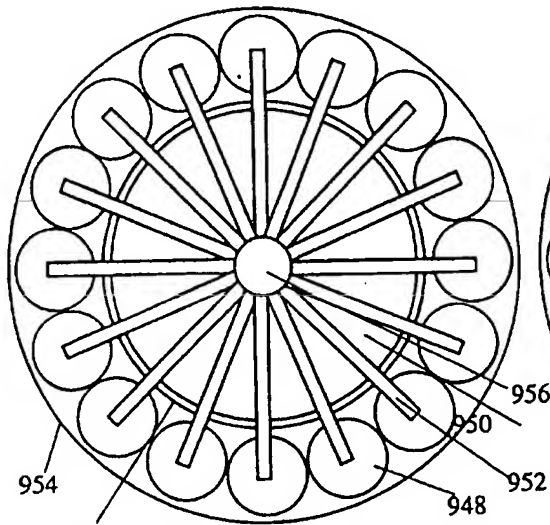


Figure 12(a)

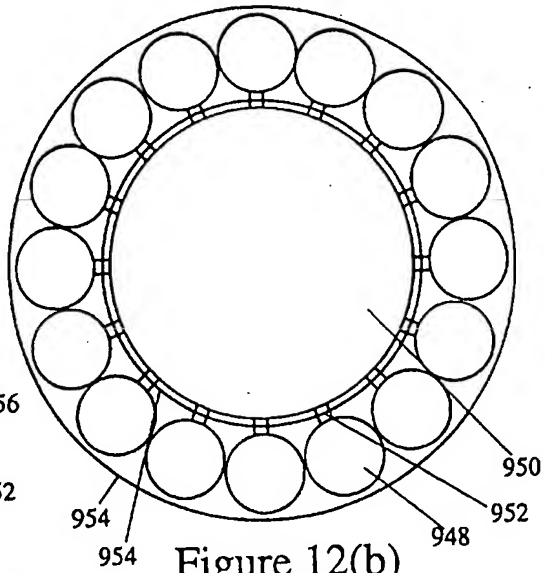


Figure 12(b)

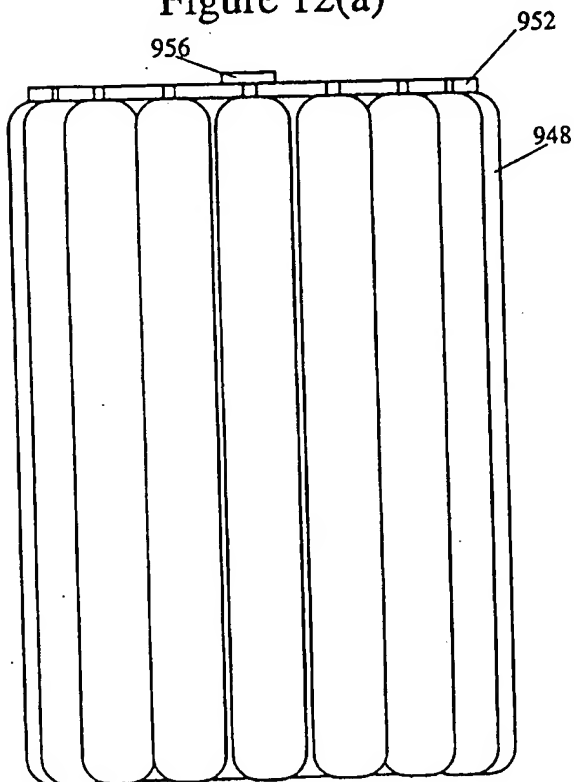


Figure 13(a)

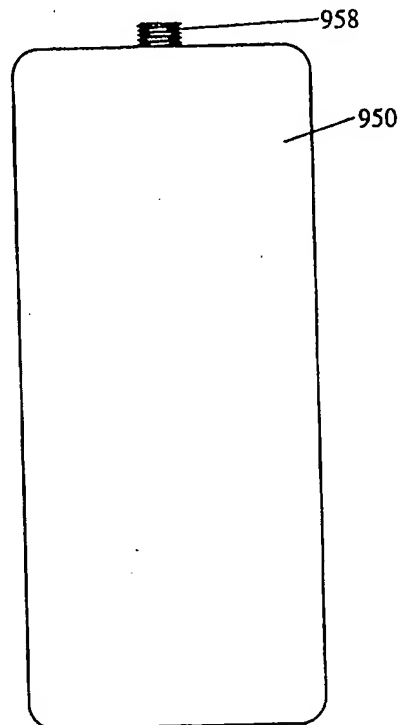


Figure 13(b)

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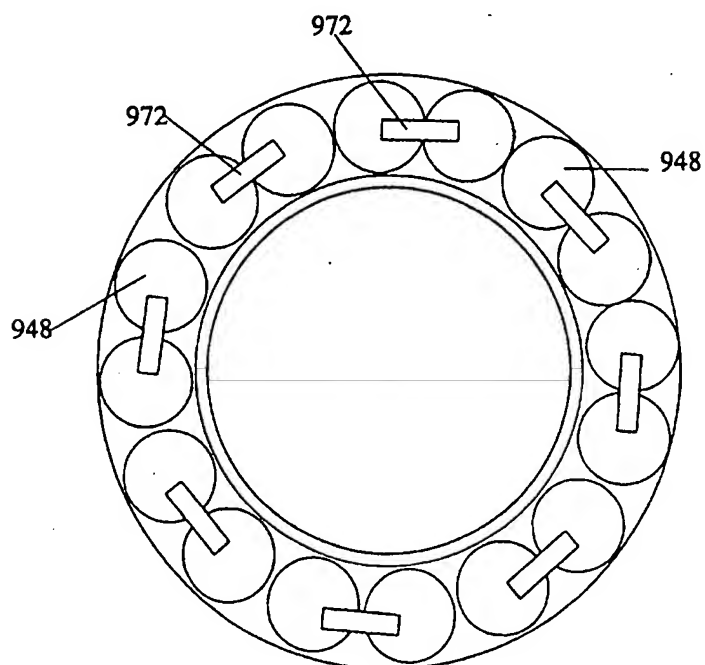


Figure 12(d)

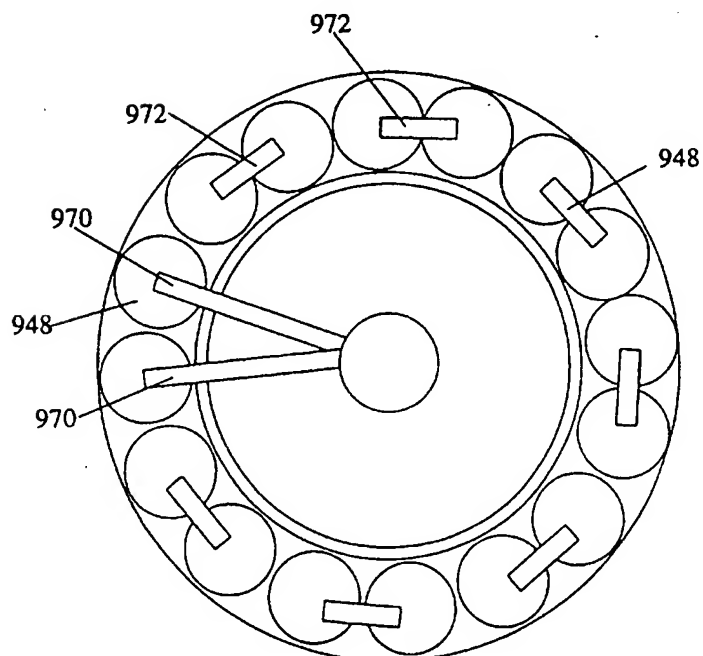


Figure 12(c)

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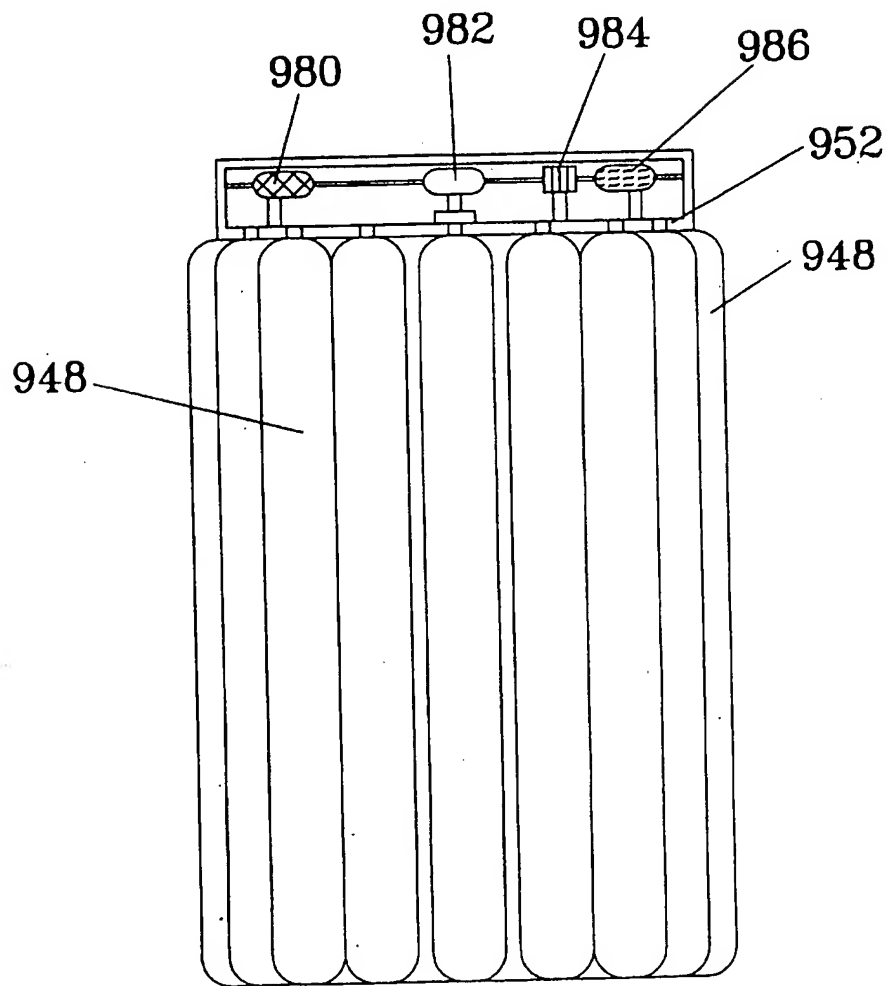


Figure 13(C)

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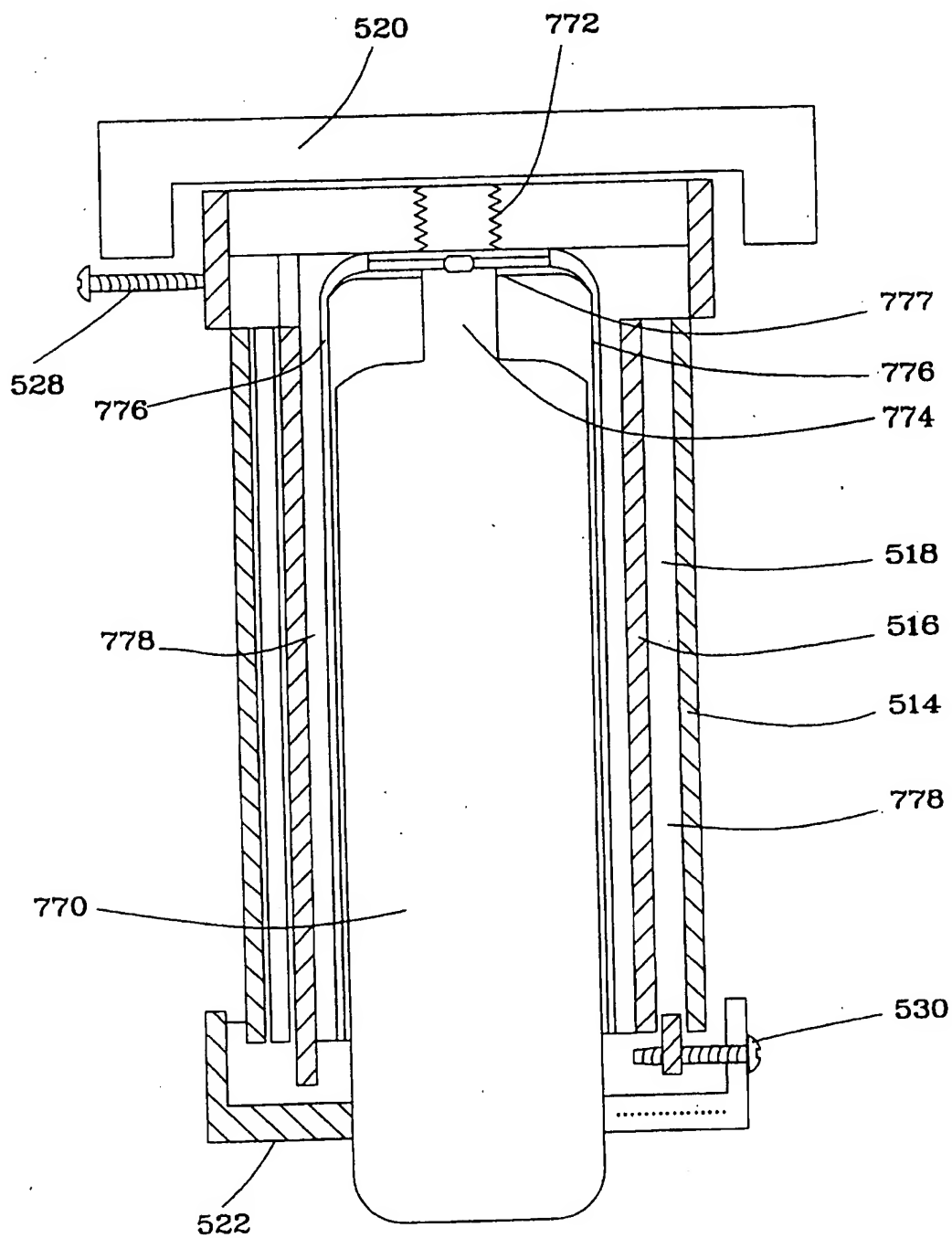


Figure 14

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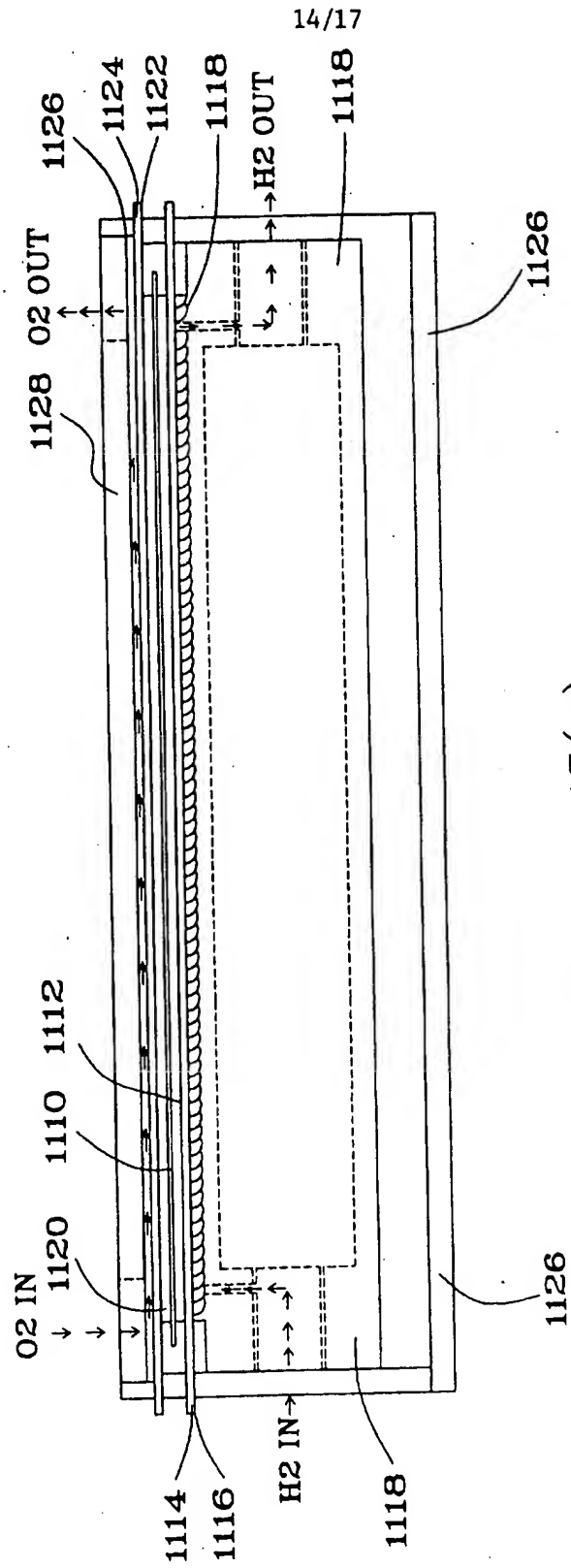


Figure 15(a)

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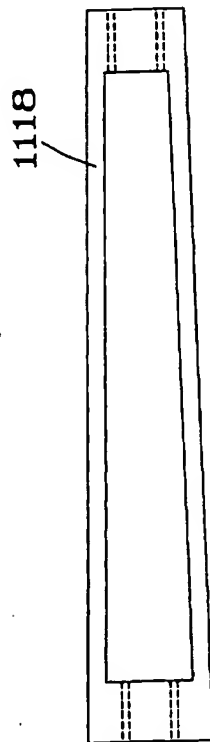


Figure 15(b)

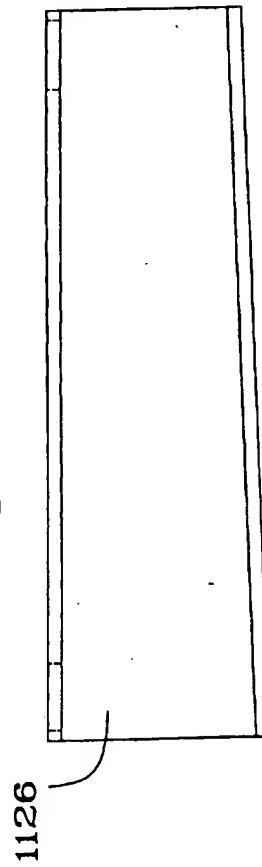


Figure 15(c)

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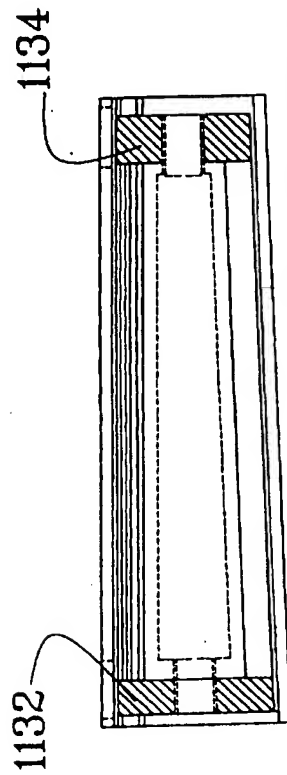


Figure 15(d)

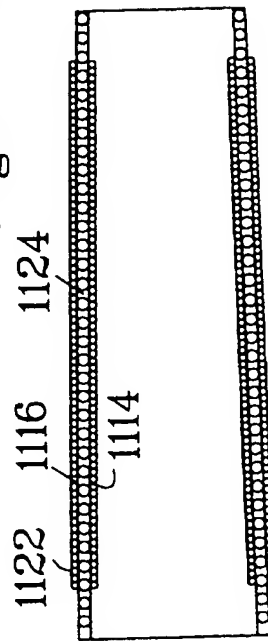


Figure 15(e)

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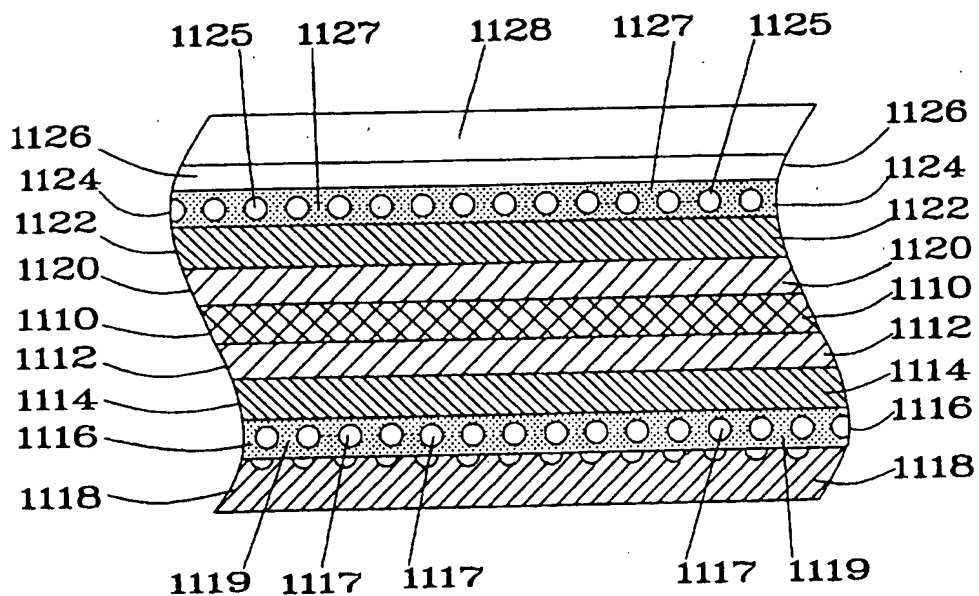


Figure 15(f)

# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US95/09947

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01M 8/10, 6/00

US CL :429/31, 33, 35; 29/6232; 427/115

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 429/30-34, 38-40, 94; 29/623.1, 623.2; 427/115

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A, 4,175,165 (Adhart) 20 November 1979.	
A	US,A, 4,477,541 (Fraioi) 16 October 1984.	
A	US,A, 4,824,742 (Parry) 25 April 1989.	
A	US,A, 4,975,342 (Matsumoto) 04 December 1990	
A	US,A, 5,171,646 (Rohr) 15 December 1992.	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:	* T	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
* A* document defining the general state of the art which is not considered to be of particular relevance	* X	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
* E* earlier document published on or after the international filing date	* Y	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
* L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	* Z	document member of the same patent family
* O* document referring to an oral disclosure, use, exhibition or other means		
* P* document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

07 DECEMBER 1995

Date of mailing of the international search report

Name and mailing address of the ISA/US  
Commissioner of Patents and Trademarks  
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Washington, D.C. 20231

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ANTHONY SKAPARS

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Form PCT/ISA/210 (second sheet)(July 1992)\*